Remote Sensing and Imaging Physics

05 March 2013

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Program Officer
AFOSR/RTB
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

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Form Approved
OMB No. 0704-0188

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1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
05 MAR 2013		**00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Remote Sensing and Imaging Physics	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Office of Scientific Research ,AFOSR/RTB,875 N. Randolph,Arlington,VA,22203**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**29**	

2013 AFOSR Spring Review
2301F Portfolio Overview

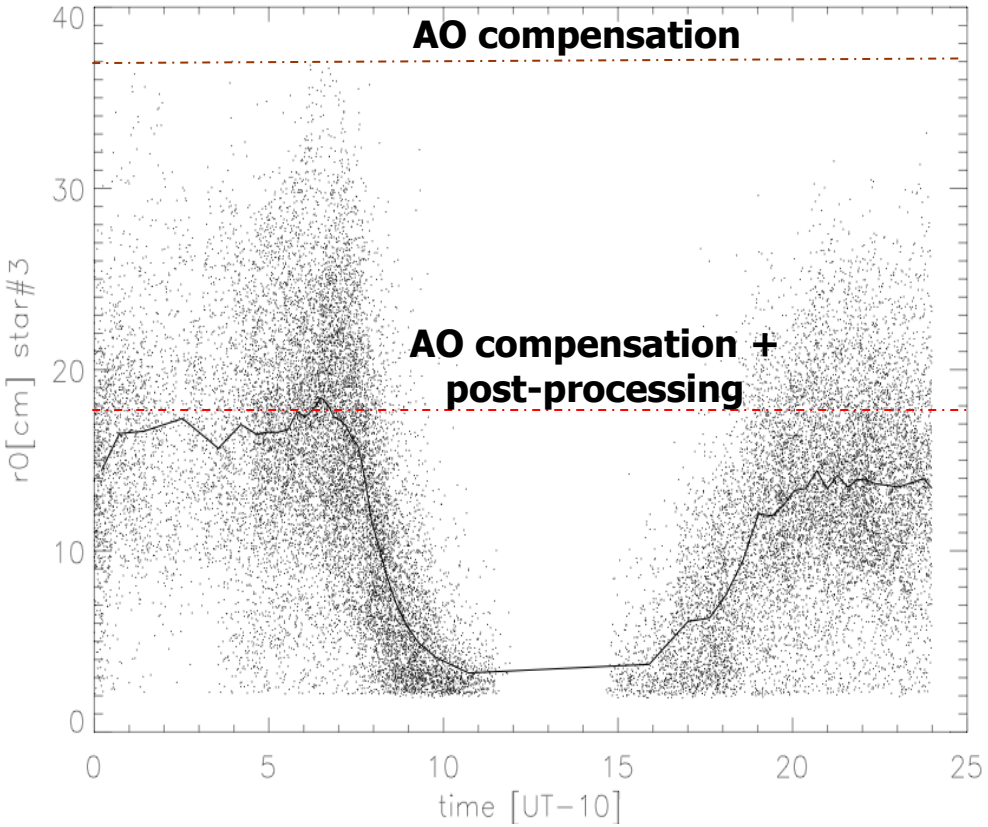
NAME: Kent Miller

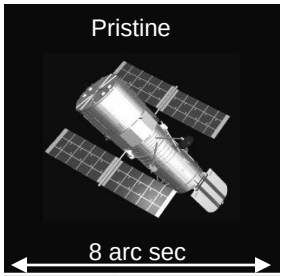
BRIEF DESCRIPTION OF PORTFOLIO:
Understand the physics that enables space situational awareness
Understand the propagation of electromagnetic radiation and the formation of images

SUB-AREAS:
1. **Imaging through Turbulence**
2. **Propagation through Turbulence**
3. **Non-Imaging Space Object Identification**
4. **Satellite Location, Tracking, and Orbit Prediction**

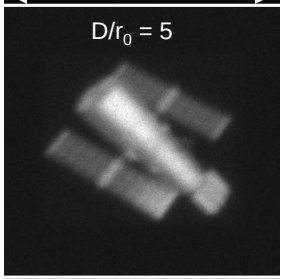
Imaging through Turbulence

Typical Imaging Conditions at 0.5 μm at AMOS

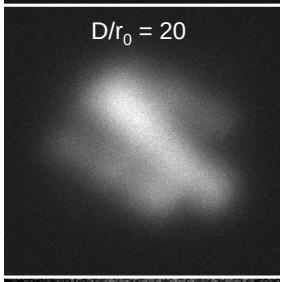




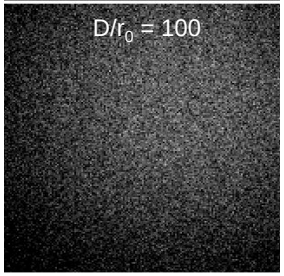
Pristine



Good Seeing Terminator



Marginal Seeing Terminator



Daytime

Simulations of the Hubble Space Telescope as it would appear from the 3.6 m AEOS telescope at a range of 700 km in 1 ms exposures at 0.9 μm wavelength under a range of seeing conditions.

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PROTEA

(Partnership for Research in Optical Technology and Estimation-theoretic Analysis)

- New image restoration methods to provide 24-hour horizon-to-horizon coverage
- Information theoretic approach to Space Object Identification
- Pre-conditioning of data to reduce computational overhead
- Understanding speckle phenomenology in Superresolution Active Modulation Imaging (SAMI)
- Modeling information communicated through the image chain

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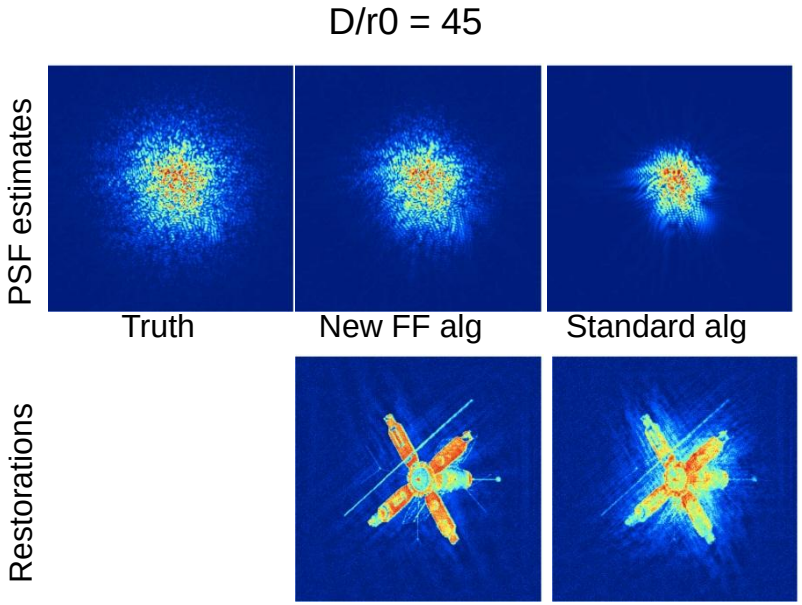
AFRL

Algorithms for Multi-Frame Blind Deconvolution

Approaches for MFBD algorithms that:

- **Enable faster convergence with higher likelihood of achieving the global minimum.**
- **Improve quality of image restorations.**
- **Extend limits of SSA imaging capabilities.**



Initial PSF Estimates using Wave Front Sensor

- WFS collects coarse grid gradients.
- Overlapping measurements, and frozen flow assumption provides finer grid approximations.
- Novel interpolation and constrained optimization algorithms reconstruct initial estimate of PSF.
- Substantial improvement over adaptive optics for high D/r_0

James Nagy, Emory University
Stuart Jefferies, U Hawaii

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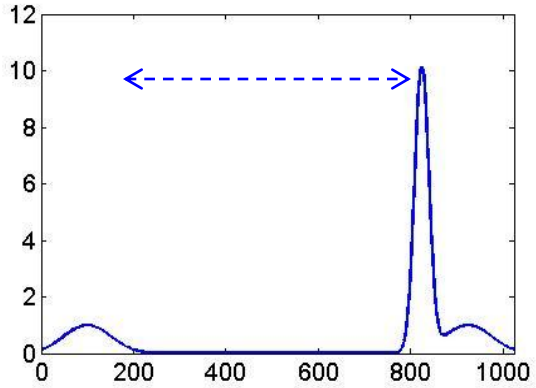
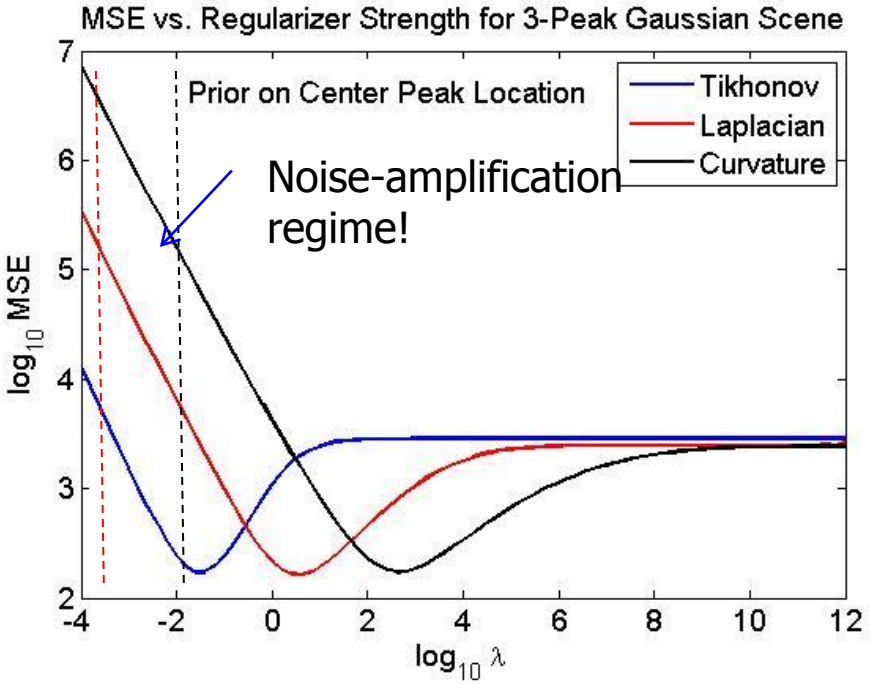
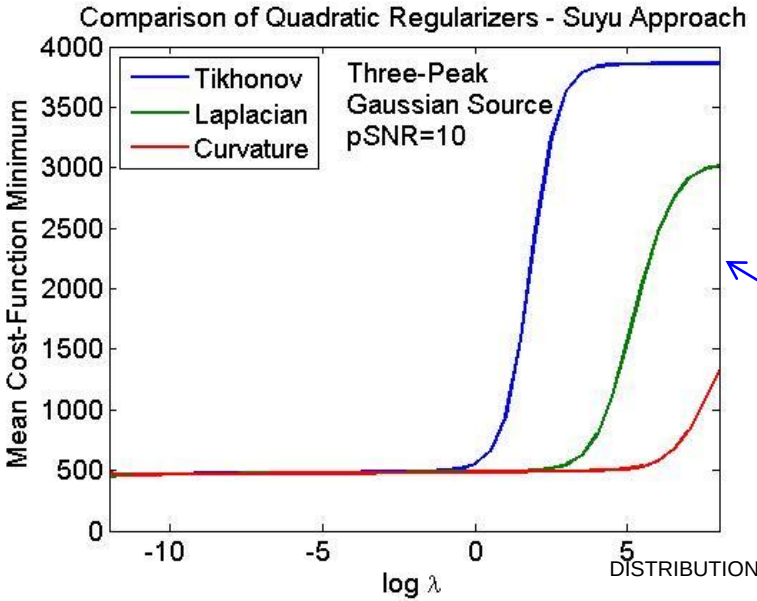
Family of 3–peak Gaussian Sources: Prior on Central Peak Location



Uniform prior on <u>location</u> of central peak





<u>Current</u> accommodation-based metric of optimality – picks curvature regularizer!

<u>Previous approach</u> - Evidence-based metric also picks curvature regularizer!

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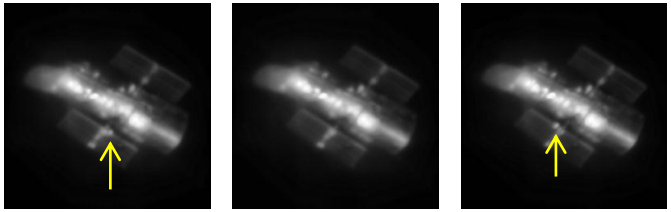
Sudhakar Prasad, University of New Mexico

Robust Image Reconstruction

Image reconstruction of spacecraft observed through atmospheric turbulence is limited by unmodeled effects such as transient glints:

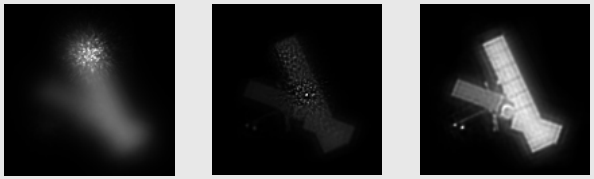


Consecutive images of HST at 10 Hz

Robust MFBD: Algorithm is iteratively reweighted blind deconvolution:

1. Assign weight to each data pixel
2. Reconstruct image using weighted data
3. Update weights where predicted image does not agree with data
4. Repeat.

Transient glints

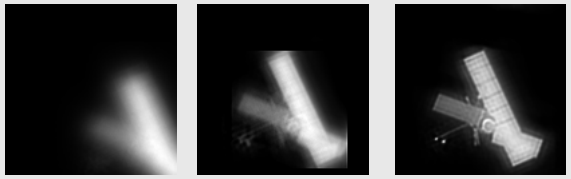


Simulated frame with glint | Traditional MFBD | New *robust* MFBD

Unmodeled noise

Simulated frame with unmodeled noise | Traditional MFBD | New *robust* MFBD

Edge effects



Simulated frame clipped at edge | Traditional MFBD | New *robust* MFBD

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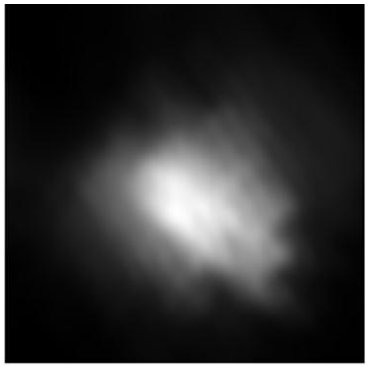
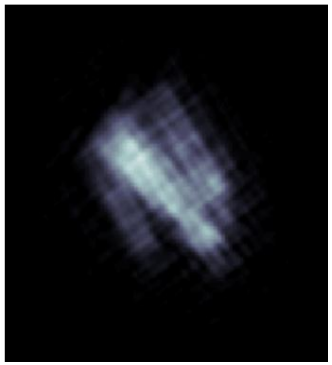
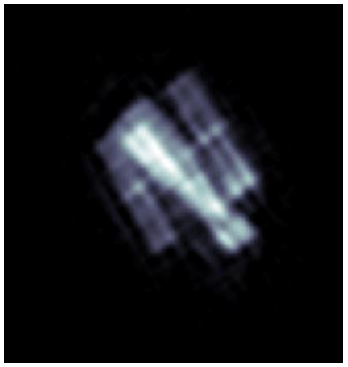
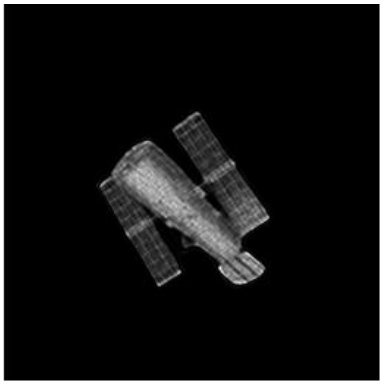
High-resolution imaging of LEO targets through strong atmospheric turbulence

D/r_0=40	2008	2010	2011	2012
				
Raw data frame	Single telescope +MFBD +Spectral nulls	Multi-telescopes +Cross-channel consistency	WFS measurements +Frozen Flow Model (FFM)	Multi-telescope +Annular partition +Multi Aperture Phase Retrieval + FFM + MFBD +WFS

Increasing synergy between data acquisition and processing

Increasing aperture diversity

Benefits for SSA: extend sky coverage and range of observing conditions

Stuart Jefferies, University of Hawaii

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Robust, flexible image reconstruction: passive sensing of objects in GEO

- Amplitude interferometry
- Intensity interferometry
- Shadow imaging

- Quantify performance limits:
  - SNR
  - Cramér-Rao Lower Bounds
  - Reconstructed image quality
  - Etc.

	PROS	CONS
Amplitude Interferometry (AI)	Higher measurement SNR compared to II, potential to measure phase information in addition to Fourier modulus	Exacting requirements for path matching/stability, ground-based version impacted by atmospheric turbulence
Intensity Interferometry (II)	Path matching/stability requirements less stringent than for AI, resolution not limited by atmospheric turbulence	Fundamental SNR is extremely poor
Shadow Imaging	SNR limited by background star not object itself	Measures object silhouette only, limited number of stars means limited observation opportunities, sensor bandwidth requirements most likely increase going to a space-based implementation

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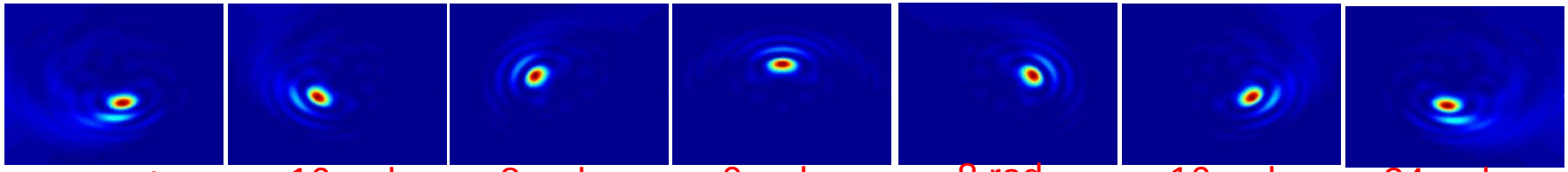
Rotating PSF via Spiraling Pupil Phase

Sudhakar Prasad, University of New Mexico

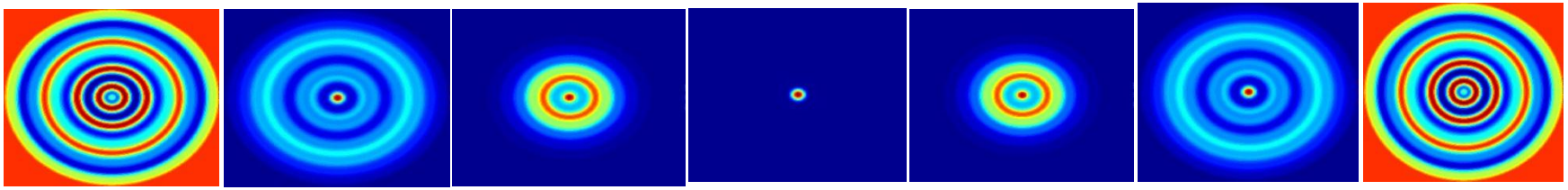
Rotating PSF (for M=7 Fresnel zones)



+24 rad +16 rad +8 rad 0 rad -8 rad -16 rad -24 rad

Changing Defocus ς

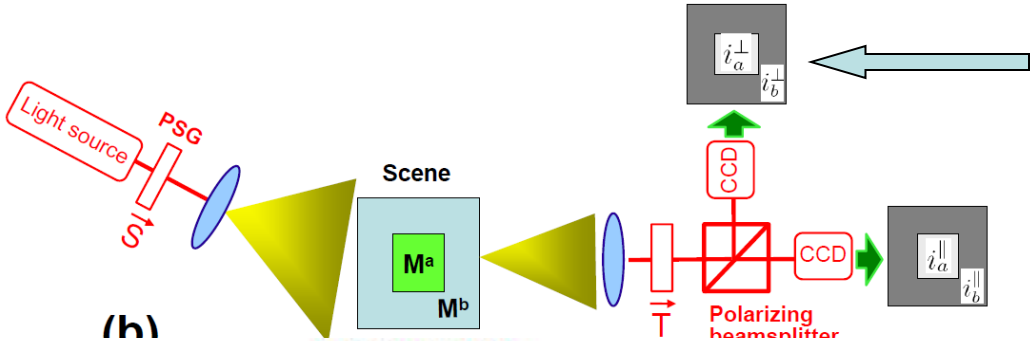
+24 rad +16 rad +8 rad 0 rad -8 rad -16 rad -24 rad



Conventional PSF – spreads dramatically, rapid loss of sensitivity!

- Rotating PSF –
  - Single-lobe PSF with relatively stable shape/size
  - High 3D image capture/reconstruction sensitivity
  - Defocus $\varsigma = \delta z.\Omega/\lambda$, $\Omega = R^2/l_0^2$, solid angle of imager at source
- SSA application –
  - Ranging of space debris relative to AF assets
  - Can reconstruct range and brightness in a crowded 3D scene

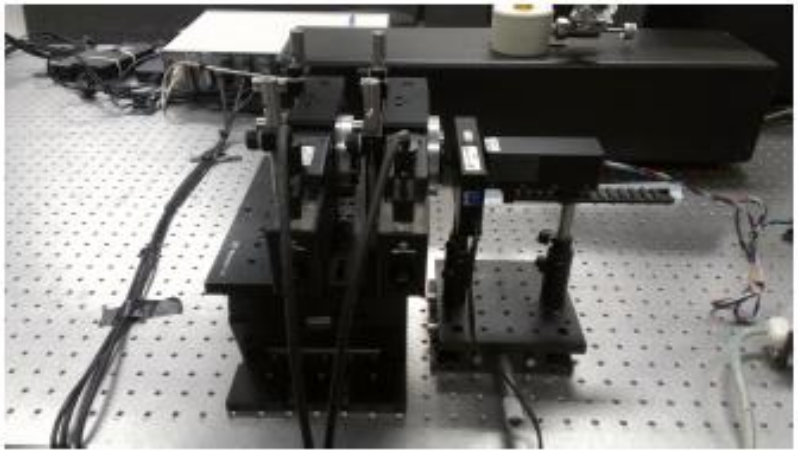
Reduced-Measurement Active Polarimetry



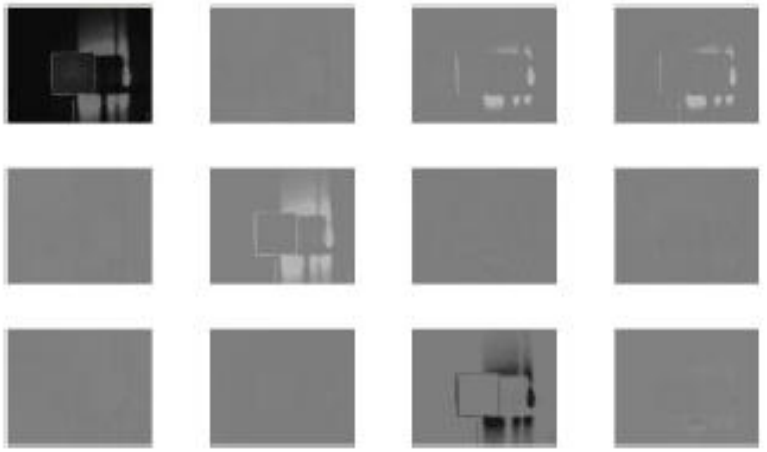
(a) SWIMMP

Full Mueller polarimetry requires at least 16 measurements.

Reduced-measurement polarimeter concepts that control illumination and analysis polarization states to maximize target contrast



(b) Image of Spectrolon from SWIMMP



Students from UA constructed an active 1.5-μm partial polarimeter at WPAFB for use in a basic research program on human signature detection. The polarimeter makes at most 12 measurements, but can be operated with a single polarized measurement. Initial lab and outdoor testing was completed in the fall of 2012, and development will continue in 2013.

Funded in 2012 to transition concepts from our AFOSR-sponsored basic reasearch to:

• AFRL/RYJT (signature detection) • USA/NVESD (IED detection) • Sunkist (Optical Fruit Grading)

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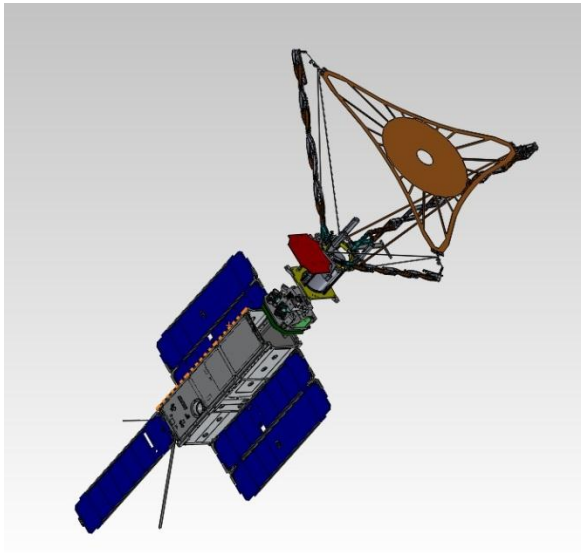
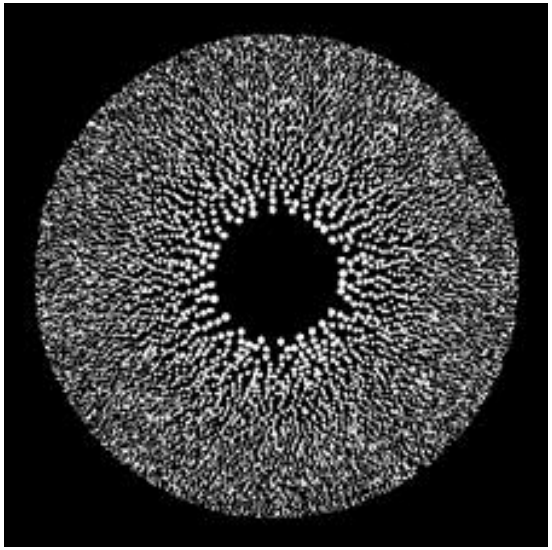
Scott Tyo, U Arizona

Peregrine: World's First Collapsible Space Telescope

- **Photon Sieve Observations of the Sun**
  - Deployed from 3U CubeSat as part of FalconSAT-7
  - 0.2m diameter, f = 0.4m l = 656.5nm (H-alpha), 2.5 billion holes!
  - Launch date of early 2015, total lifetime cost of $1.5 million





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Projective Quantum Measurements on Spatial Modes of the Optical Field

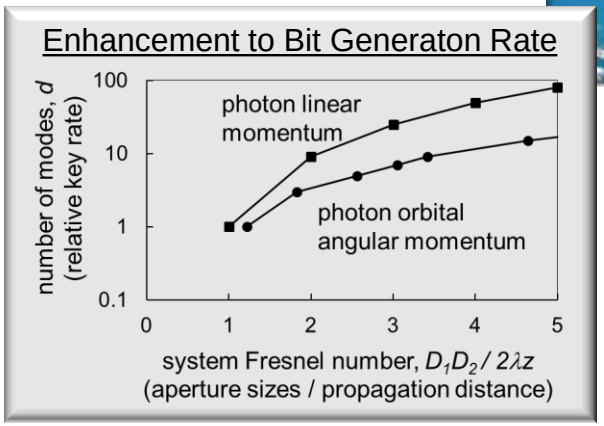
Quantum Key Distribution (QKD) for generation of encryption keys over free-space optical links

Problem:

- Optical losses in free-space quantum channels slow key generation rates

Approach:

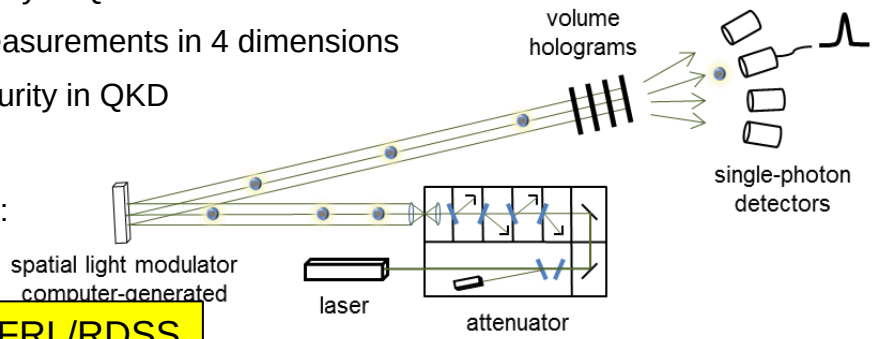
- Increase information carrying capacity of single photons
- Exploit spatial attributes (a.k.a. linear and orbital angular momentum quantum states) of the photon wave function
- Develop transmission volume holograms as quantum projection operators in order to utilize spatial modes in a QKD protocol.

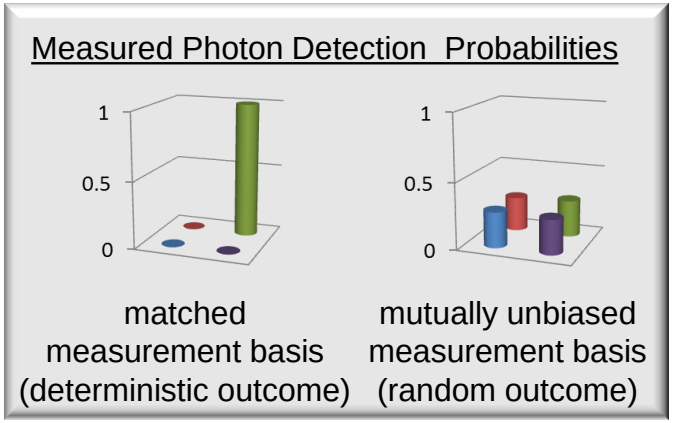


To date, have demonstrated:

- Deterministic photon measurements in 4 dimensions
  - provides fidelity in QKD
- Random photon measurements in 4 dimensions
  - provides security in QKD

Experimental Results:





Mark Gruneisen, AFRL/RDSS

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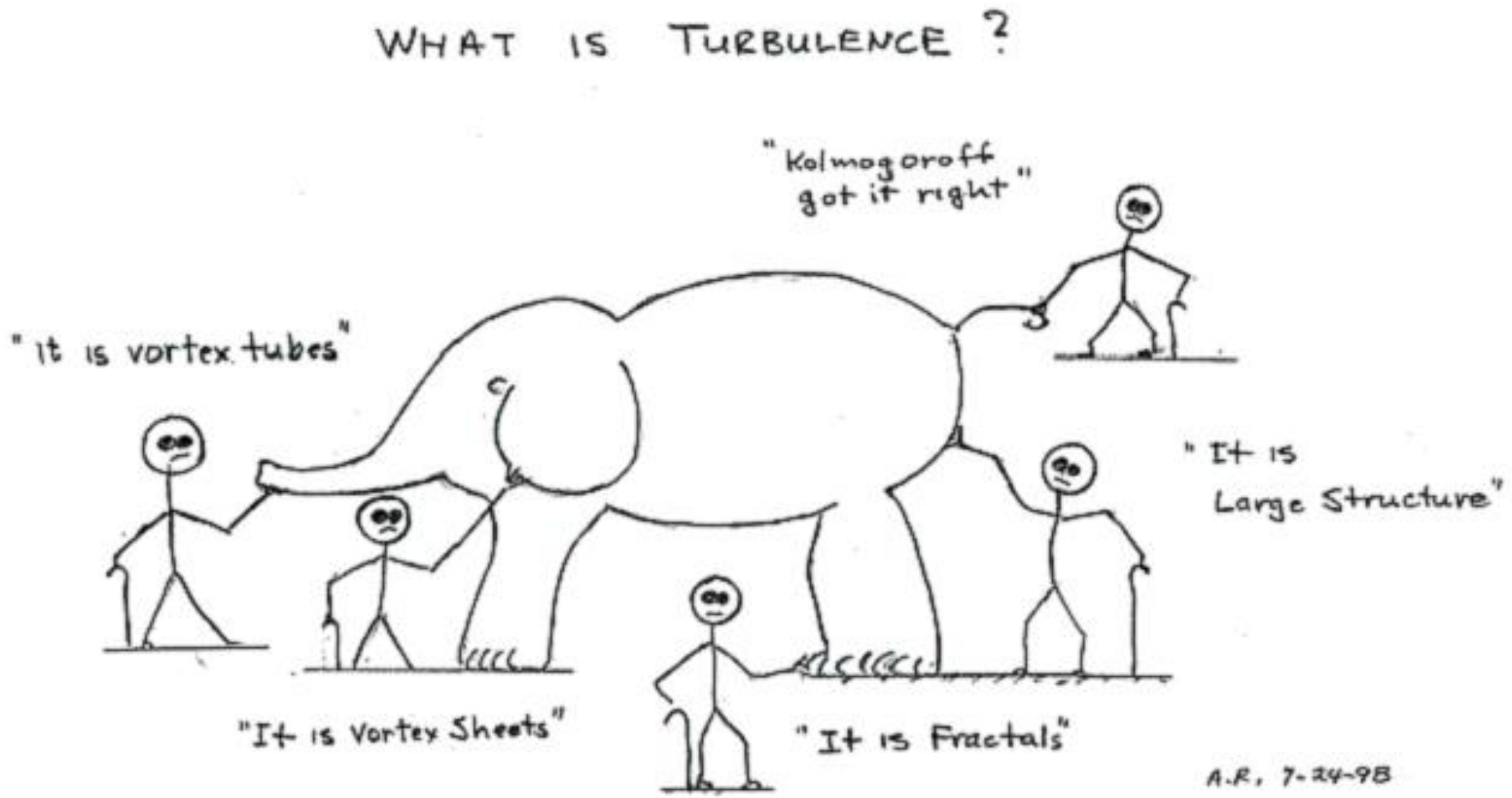
Beam Control through Turbulence



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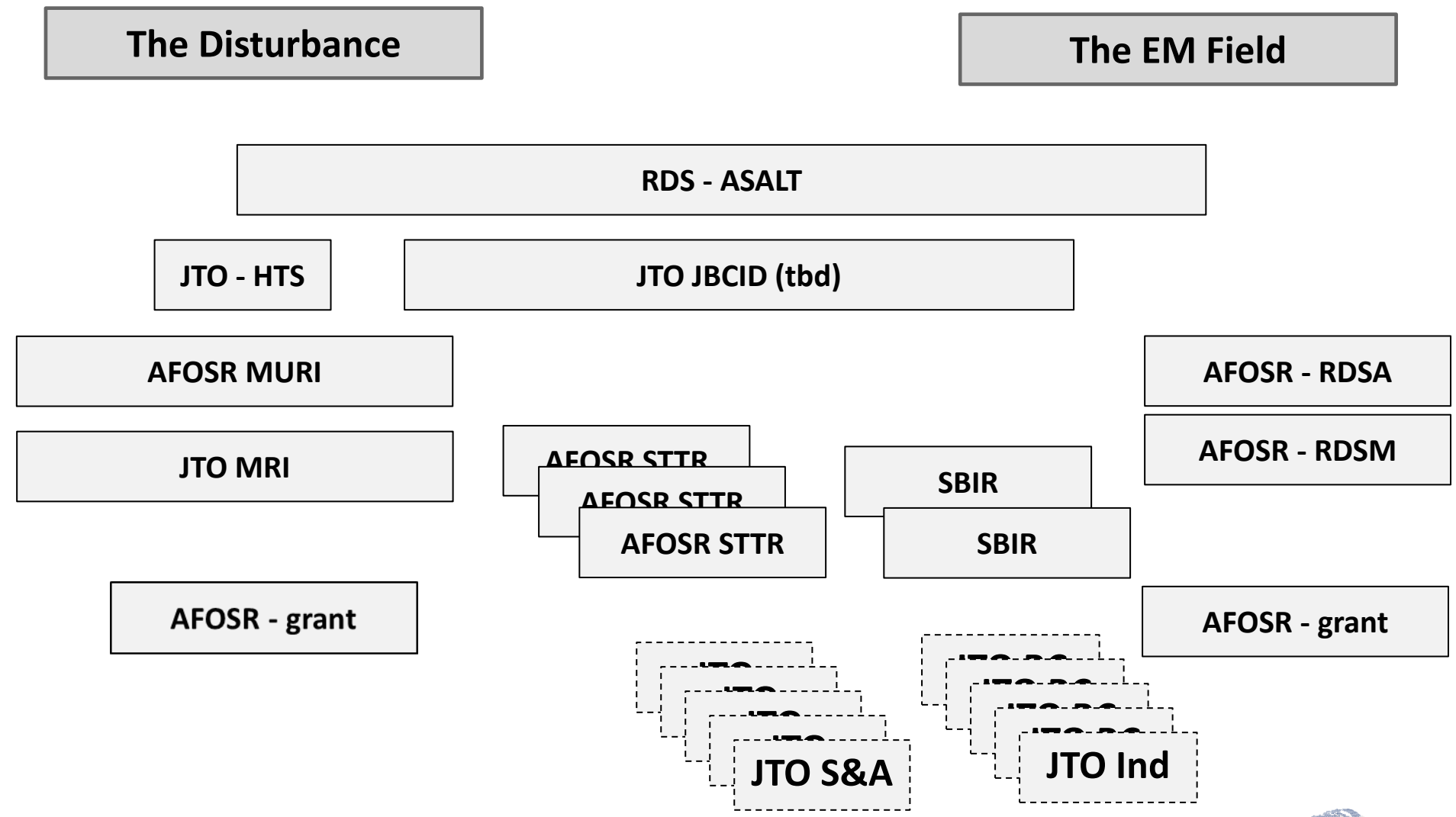
Overview of AFRL & JTO Efforts



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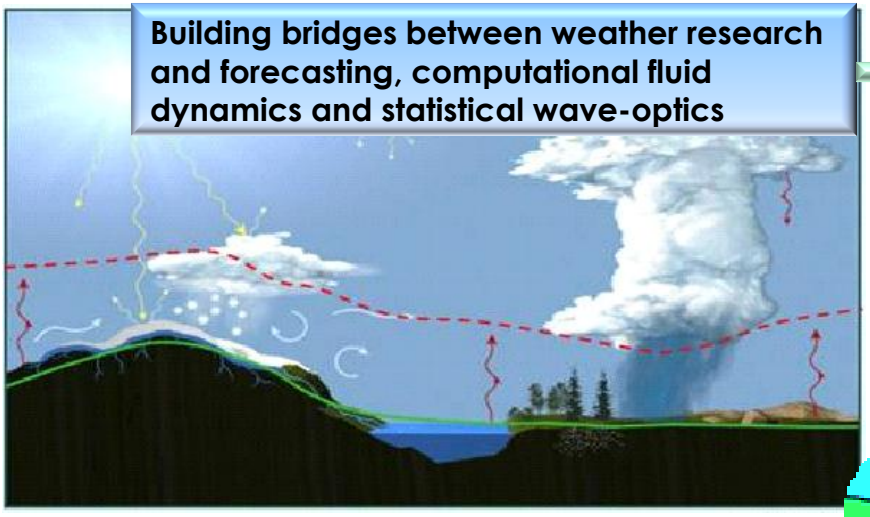
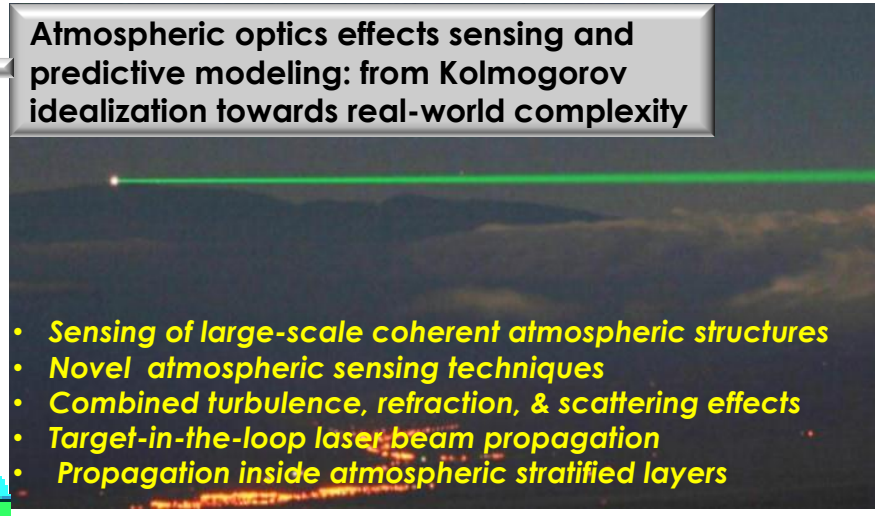
Wave Optics of Deep Atmospheric Turbulence: From Underlying Physics towards Predictive Modeling, Mitigation and Exploitation

Co-Investigators and Institutions: M. Vorontsov (UD), S. Fiorino (AFIT), M. Roggemann (MTU), S. Basu (NCSU), D. Voelz (NMSU), O. Korotkova (UM)

Building bridges between weather research and forecasting, computational fluid dynamics and statistical wave-optics

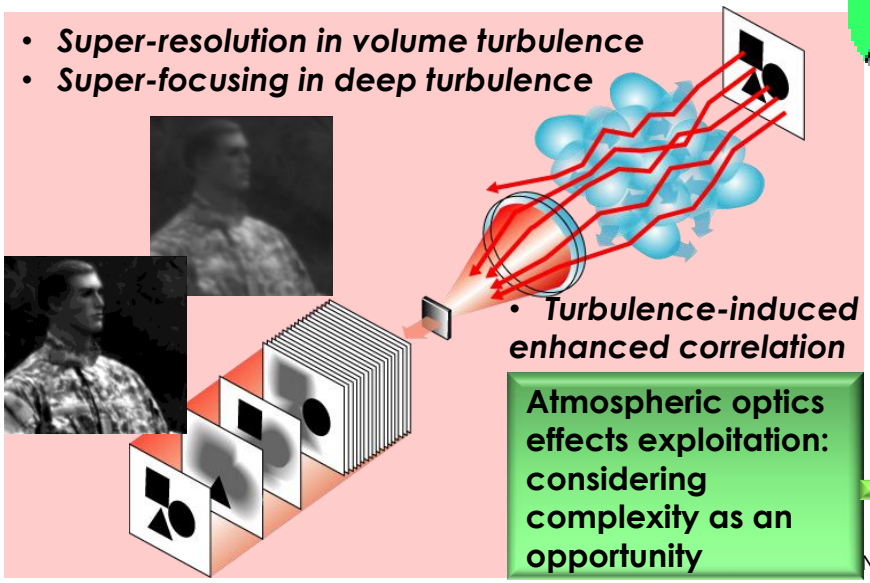


Atmospheric optics effects sensing and predictive modeling: from Kolmogorov idealization towards real-world complexity



MURI

- *Super-resolution in volume turbulence*
- *Super-focusing in deep turbulence*



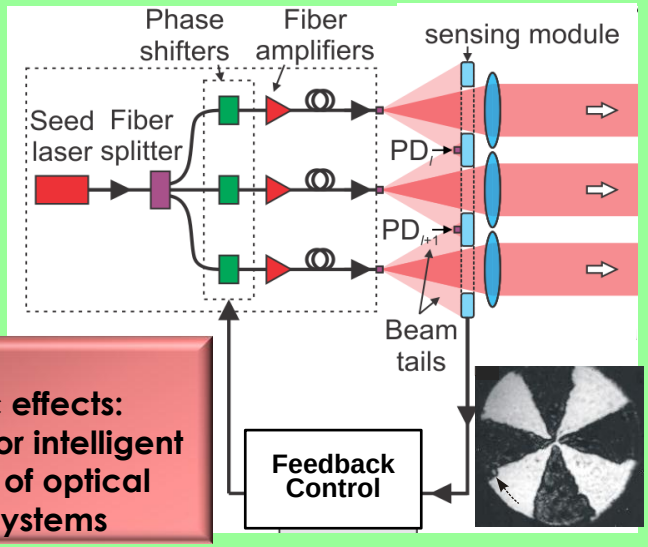
Atmospheric optics effects exploitation: considering complexity as an opportunity

Turbulence mitigation

Sparse AO

Exotic beams

Controllable coherence



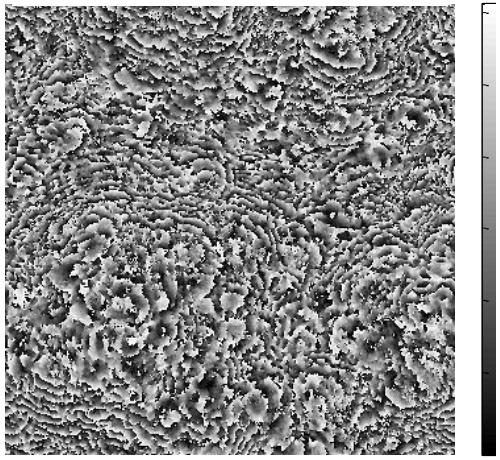
Mitigation of atmospheric effects: foundation for intelligent engineering of optical waves and systems

N STATEMENT A

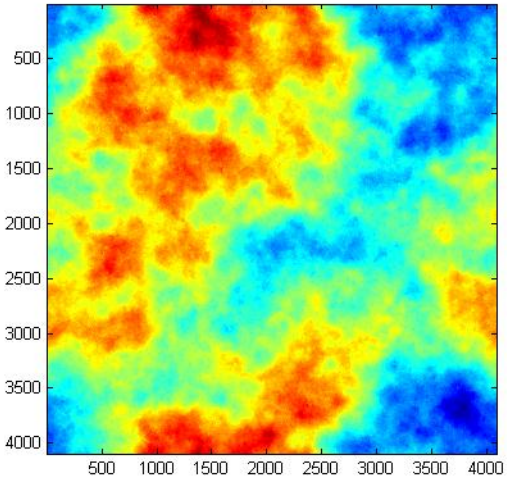
How Deep is "Deep Turbulence?"

1) Cumulative effects of wave length, path length and optical turbulence level (C_n^2)
2) Saturation of the normalized variance of intensity fluctuations.
3) As intensity variance is saturated, must use phase information.
4) Initially estimate both the C_n^2 and outer scale from at short path or using long wavelength at low a Rytov value
5) Use this outer scale value and the reconstructed unwrapped phases in the presence of branch cuts to estimate C_n^2 at deep turbulence levels (saturation).

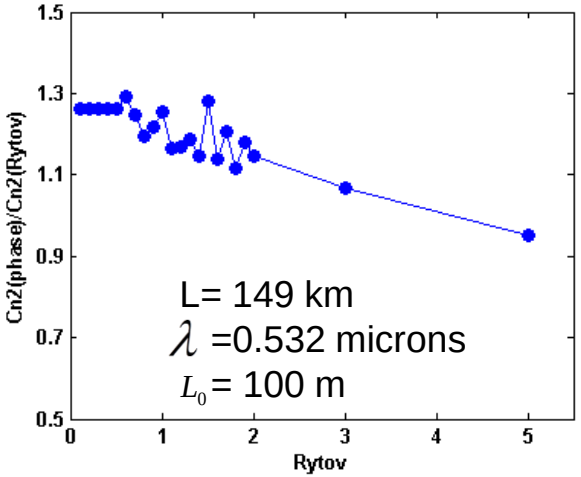
Initial Masked Phase



Unwrapped Phase



C_n^2(phase)/C_n^2(Rytov) vs. Rytov



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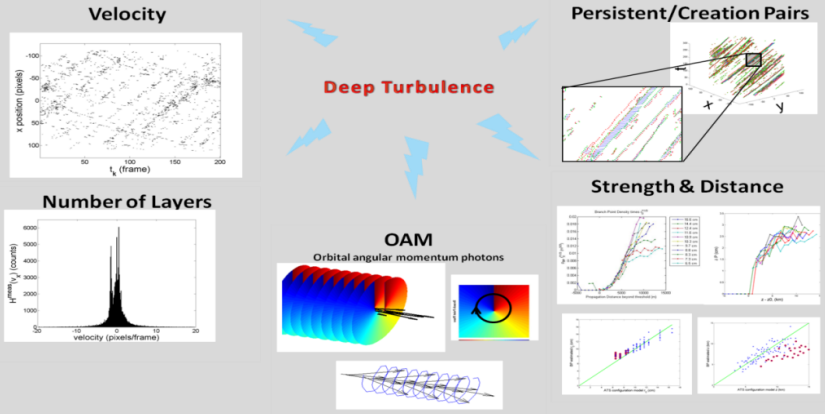
Physics of Distributed Volume Turbulence

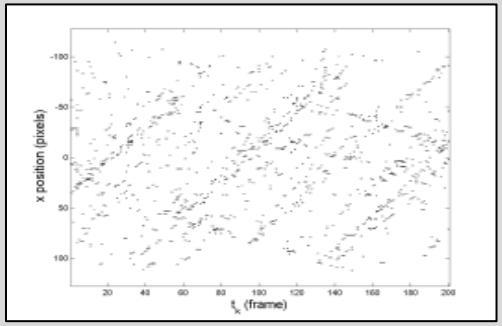
U.S. AIR FORCE

Apply four years of results to field tests

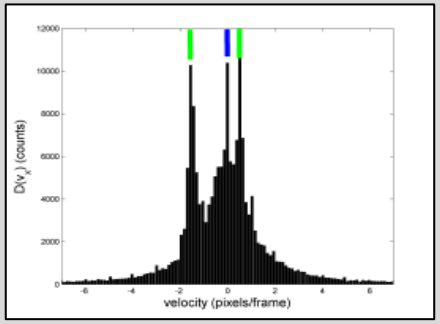


Lab Data (Phase Screens)

Branch Point Trails



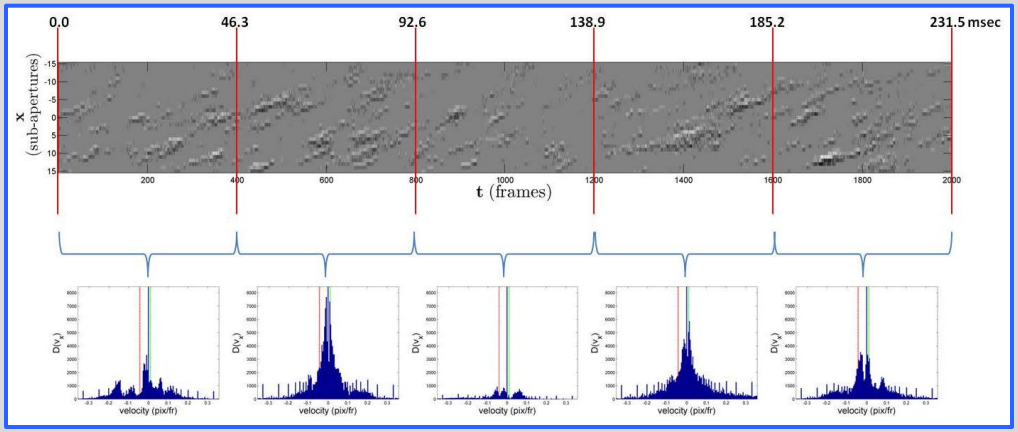
Velocity Distribution



Problem

- Laboratory and simulation results
  - assume highly controlled conditions
  - assume phase screens
  - use scintillation resistant WFS
- How will "real" turbulence affect the results?

Field Data (Distributed Volume Atmosphere)



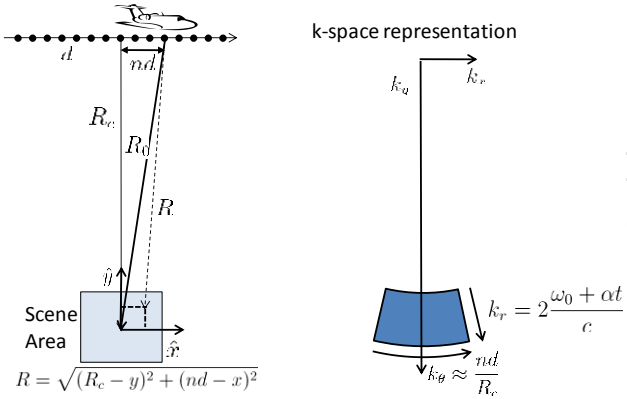
Darryl Sanchez, AFRL/RD

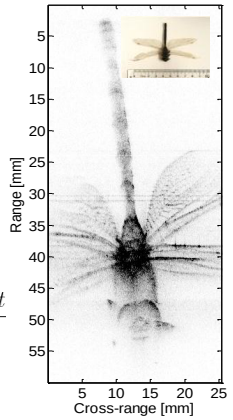
Field tests corroborate theory-lab-sim results

ASALT
The Next Generation in Adaptive Optics

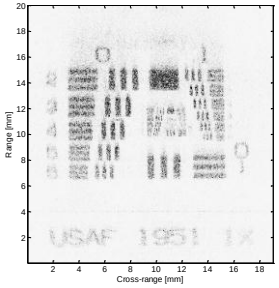
DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution

YIP: SAL Imaging and Atmospheric Turbulence



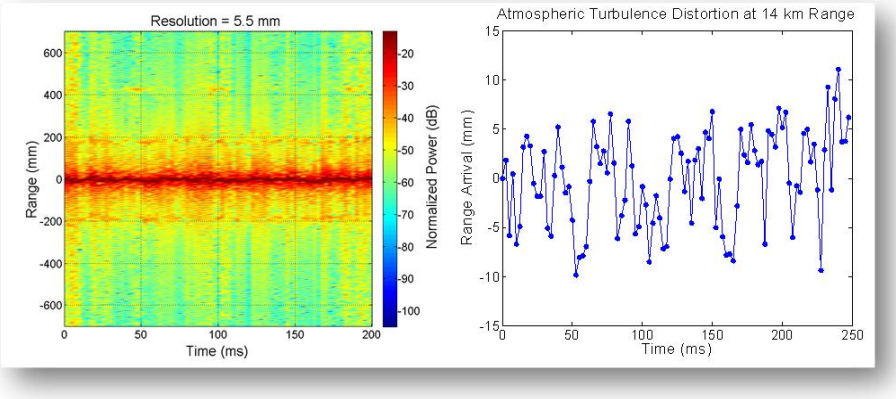


Example table-top SAL images made by MSU-SL with broadband chirped lasers



Use high resolution FMCW ladar tools to study synthetic aperture ladar (SAL) imaging, atmospheric turbulence, and their interaction.

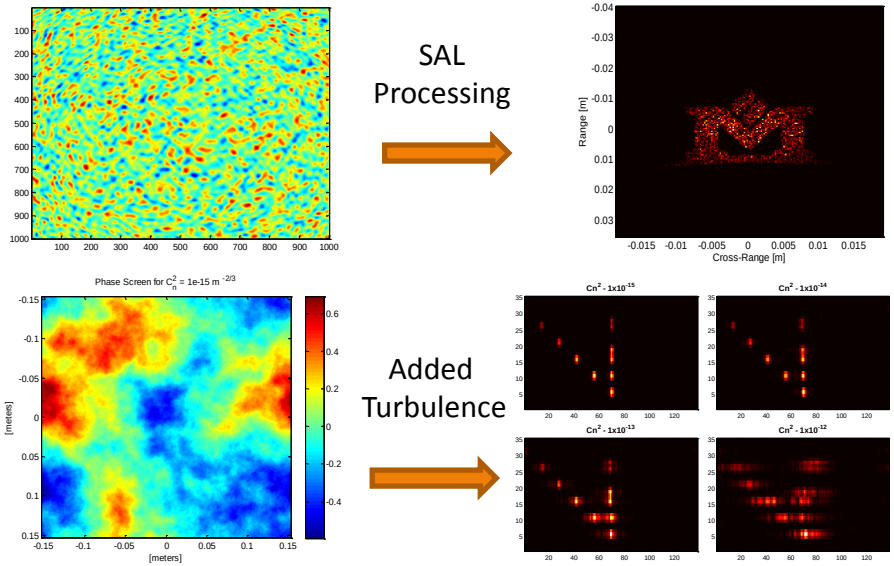
Atmospheric Turbulence



(Left) Peak range vs. time shows several mm of apparent movement

(Right) FMCW ladar history of atmospheric turbulence induced motion at 14km slant range.

SAL and Turbulence Simulations



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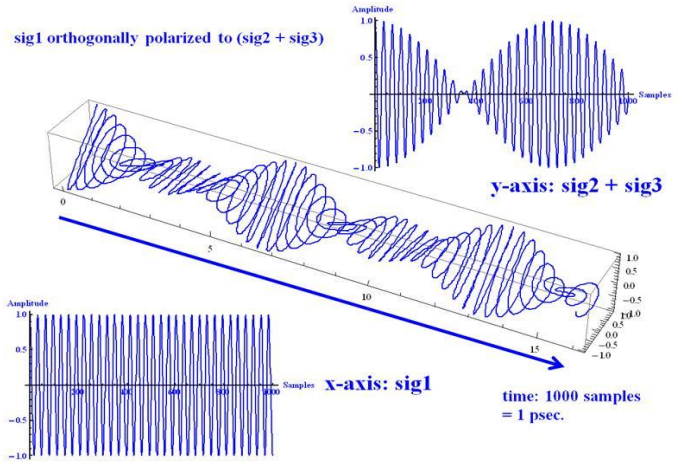
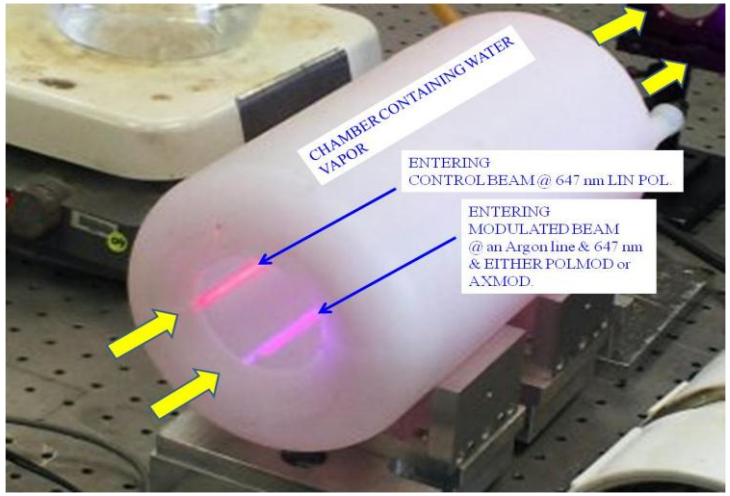
Zeb Barber, Montana State U

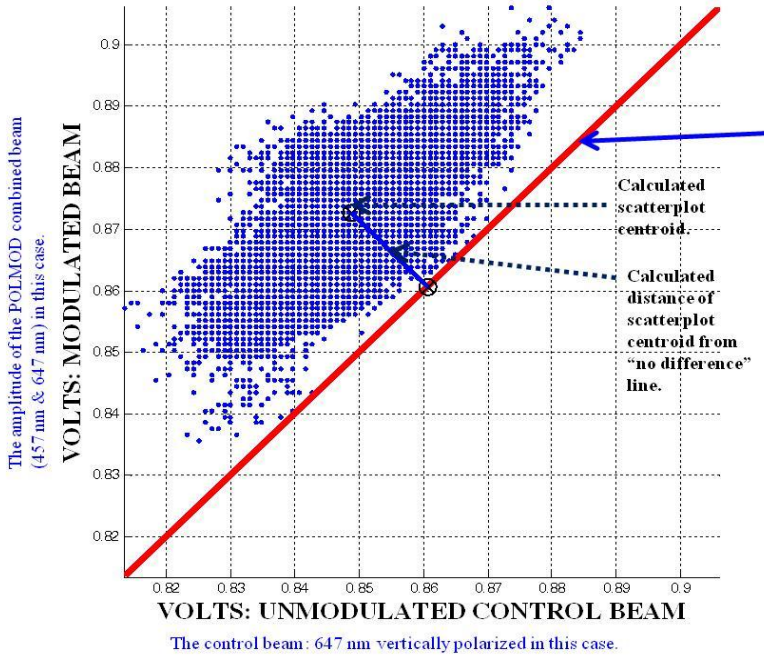
Spectrum LAB Montana State University

Propagation of Polarization-Modulated Beams through a Turbulent Atmosphere



POLMOD achieved by combining two orthogonally polarized beams of different wavelength.





"Line of No Difference" Above this line modulated beam is higher amplitude than control beam.

Imaging through Turbulent Media

Phase Conjugation in Resonantly-Enhanced Second-Order Nonlinear Materials

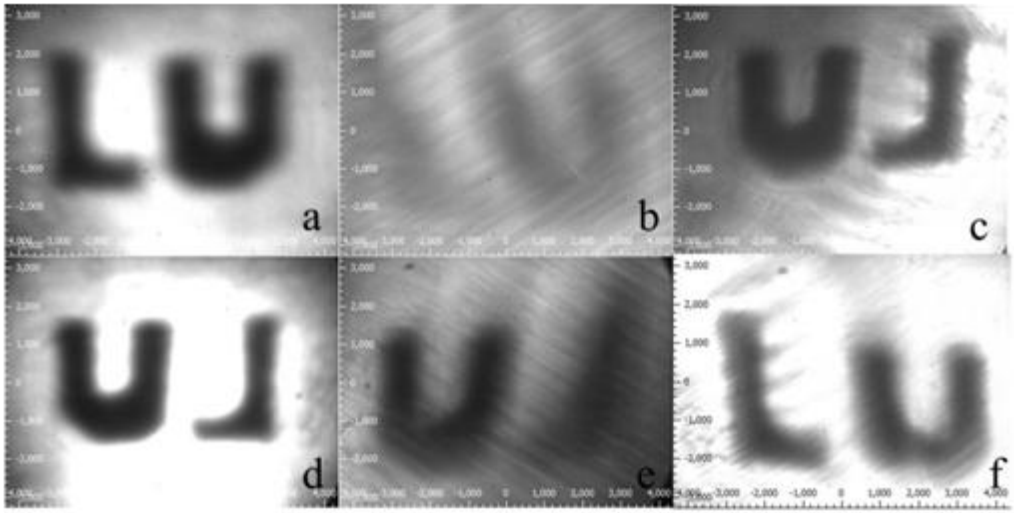
Blurred images caused by atmospheric turbulence can be completely restored to their original resolution

Measure reflecting phase-conjugate wave, after passing through turbulent medium

Theory: Y. J. Ding, Opt. Lett. 37, 4792-4794 (2012)

Advantages:

Polarization-insensitive
Low pump powers required by using second-order nonlinearity
Response is instantaneous
– suitable for correction of blurred images caused by atmospheric turbulence



Images before phase distortion for (a) *P*-polarized and (d) *s*-polarized input beam

(b) and (e) corresponding images after phase distortion

(c) and (f) corresponding images restored by phase-conjugated beams

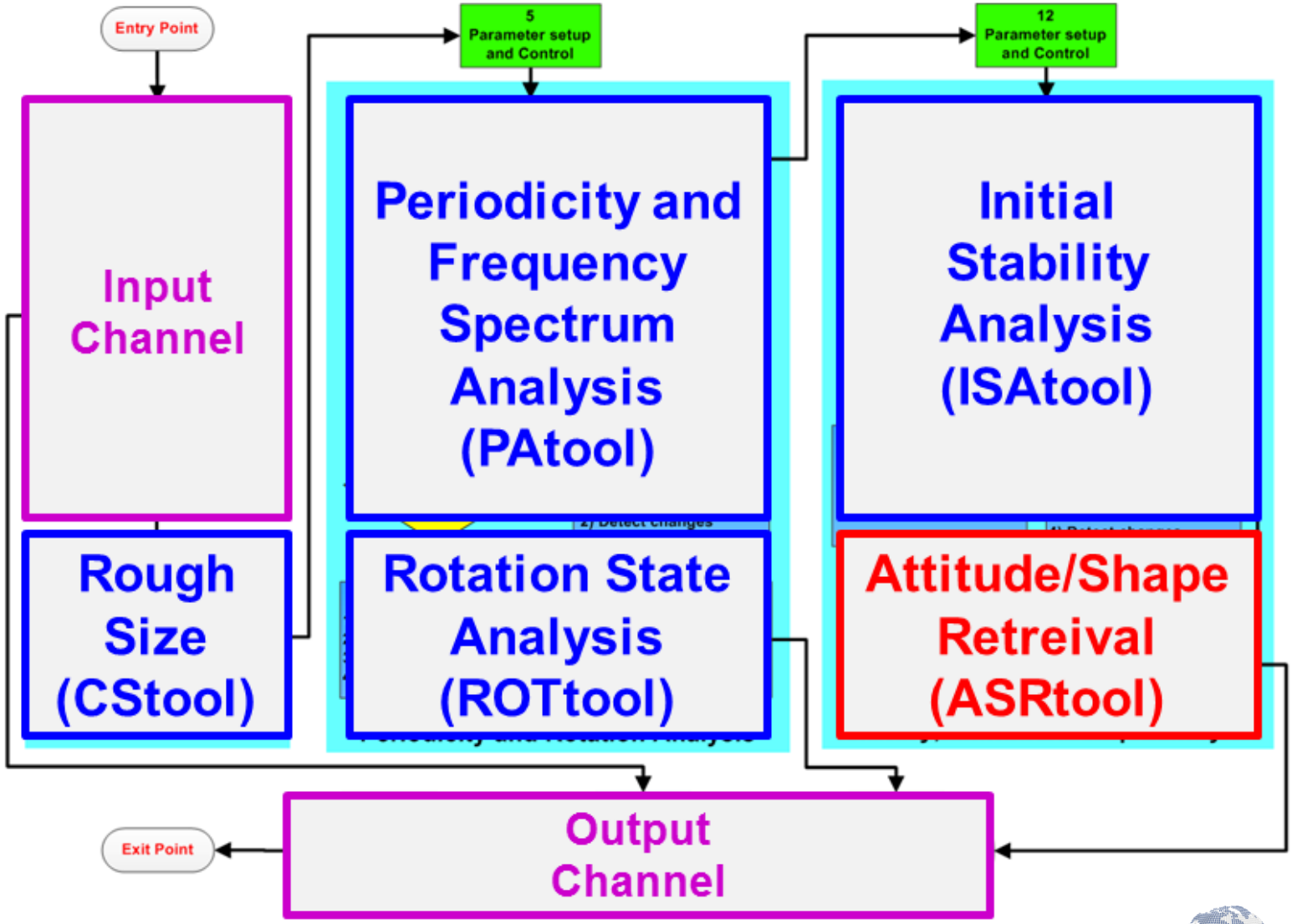
DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution

STTRs

- **Phase I**
  - **Subaperture Adaptive Optics for directed energy phased arrays**
  - **Complex field atmospheric sensing suite for deep turbulence research**
- **Phase II**
  - **Beam Control for Optical Phased Array Transceivers**

DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution

Non-resolved Space Object Identification
Ibex Software for GEO Characterization



Color Legend

6.1-level algorithm funded by:

AFOSR (previous)

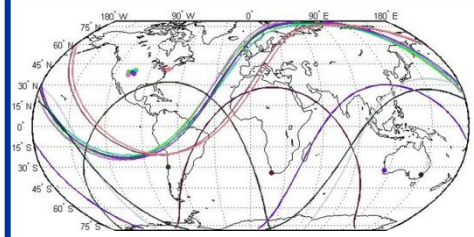
AFOSR (ongoing)

DARPA (Ibex)

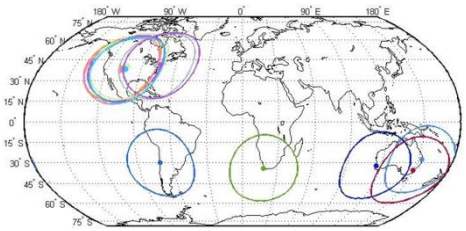
DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution

DURIP:
Falcon Telescope Network

- Global Network of small telescopes
  - Non-resolvable space object characterization
  - Satellite metrics and debris studies
  - Sensor networking
- Robotic and automated
- 13 fixed and 2 mobile sites
- Planned IOC: 2013-2014

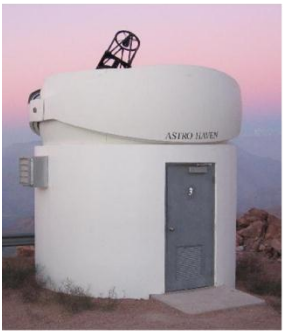


Global Coverage (GEO)



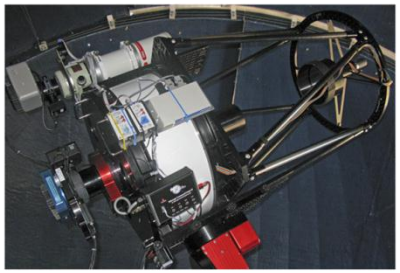
Global Coverage (LEO, 1000 km)

FTN Observatory Configuration

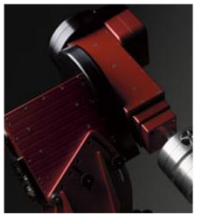


12-foot Clamshell

20-inch Telescope Truss



Paramount ME



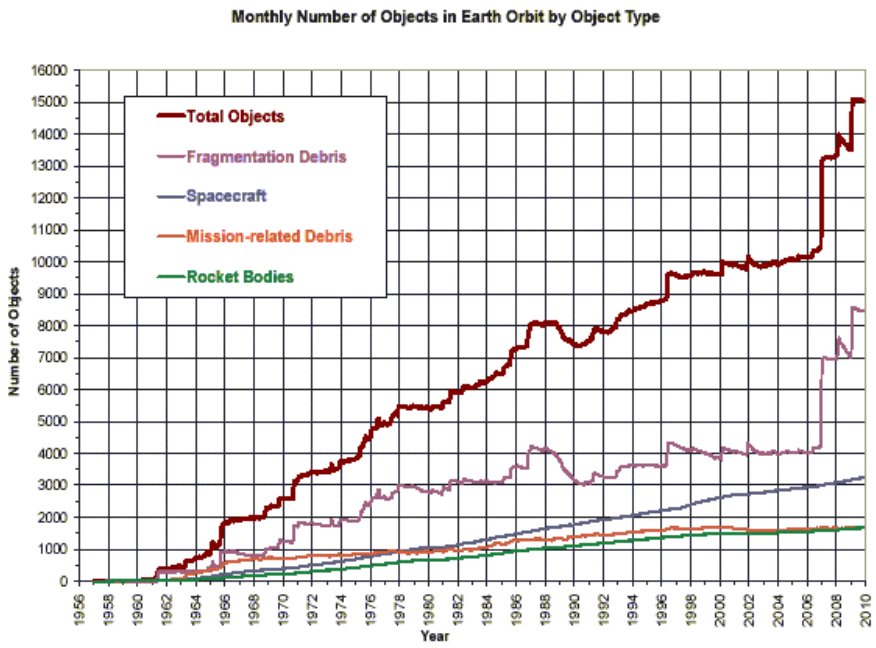
Boltwood Cloud Sensor

Filter Wheel + Apogee F47 =

Partners

- U.S
  - Colorado Mesa University (Grand Junction, CO)
  - Fort Lewis College (Durango, CO)
  - Northeastern Junior College (Sterling, CO)
  - Otero Junior College (La Junta, CO)
  - Penn State University (State College, PA)
- Chile
  - Universidad de La Serena (La Serena) & Observatorio Mamalluca (Vicuña)
- Australia
  - University of Queensland (Brisbane)
  - Catholic Education Office of Western Australia and Curtin University (Perth)
  - University of New South Wales & EOS (Canberra)
- Potential: South Africa, Kauai Community College, International Space University

Accurately Predicting the Location of Space Objects



Cornerstone capability to all SSA

- **Challenges:**
  - **Large number of objects (> 20,000 of size greater than 10cm)**
  - **Limited observations from multiple sensors**
  - **Non-Gaussian errors, uncertainty analysis**
  - **High fidelity models representing space weather**
  - **Conjunction analysis (combinatorial problem)**
  - **Closely spaced objects**
  - **Data association from diverse sensors**
  - **Optimal sensing for maximum information gathering and hazard assessment in a timely manner**
  - **Efficient computations**

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Accurately Predicting the Location of Space Objects

John Junkins (TAMU) – Insights to understand, quantify, and speed up convergence using modified Chebyshev/Picard Iteration

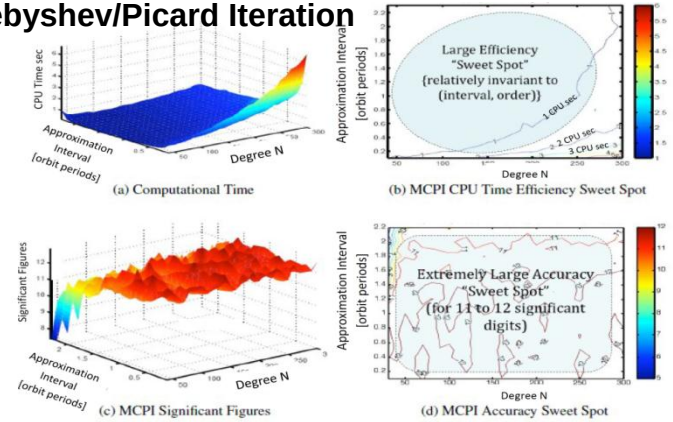
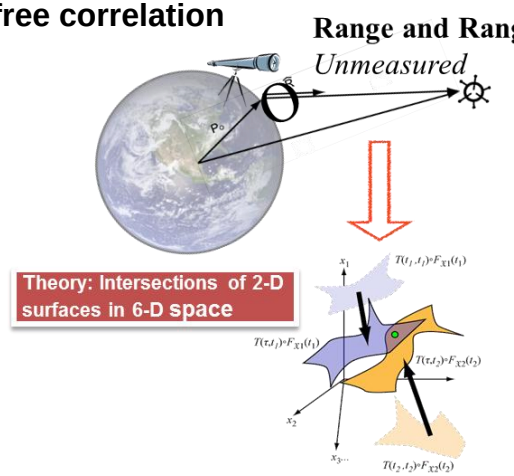
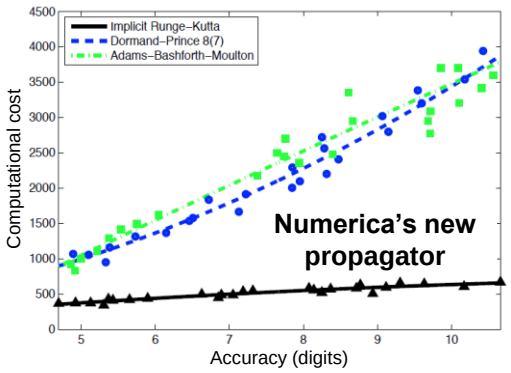


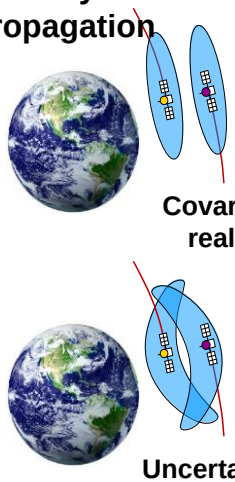
Figure 2 LEO Orbit Computation Tradeoffs:
CPU Time Versus Accuracy Versus Approximation Order Versus Length of Path Interval
(Degree varying from 40 to 300, Path Interval from 0.01 to 2.2 orbit periods)

Dan Sheeres (U Colorado) – Correlation of and change detection in space objects using non-Gaussian PDFs for hypotheses-free correlation

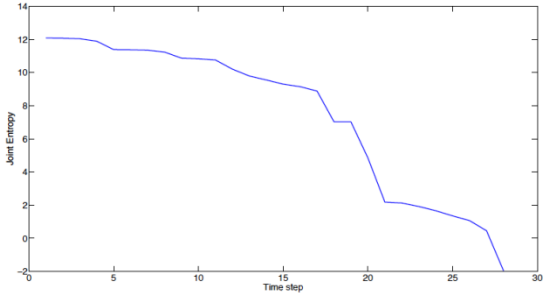


Aubry Poore/Josh Horwood (Numeric Corp.) – Highly stable, parallelizable, super-convergent family of orbital propagators for orbit and uncertainty propagation





Puneet Singla (YIP – U Buffalo) – Pose as stochastic control problem for collection and fusion of large number of objects



Decrease in mutual entropy

STTRs

- **Phase II**
  - **Time series prediction for satellite ballistic coefficients**
  - **Realistic State and Measurement Error Uncertainty Computation and Propagation for Space Surveillance and Reconnaissance**
  - **Innovative Earth Gravity Reformulation and Numerical Integration for Responsive SSA**

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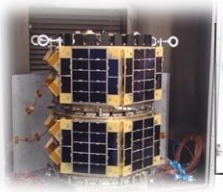
Growth of UNP Flight Opportunities

NS-1/2: 3-CornerSat
Launched: Delta-4

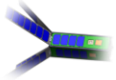
NS-3: FASTRAC
Launched: STP-S26

NS-5: DANDE



NS-6: Ho'oponopono

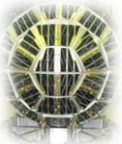
NS-7: Armadillo



NS-6: Oculus-ASR
Launch: TBD

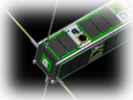
Launch: ELaNa

NS-4: CUSat

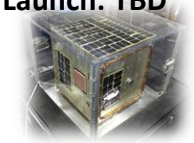


NS-6: Copper

NS-7: CADRE



NS-6: Violet
Launch: TBD



NS-7: ARGUS

2004	2010	2013	2013-2015

NS-1/2
Arizona State - W
New Mexico State - W
U Colorado-Boulder- W
Stanford University
Boston University
Carnegie-Mellon
Utah State
Virginia Tech
Washington University

2003 NS-3
UT Austin - W
Washington U - St. Louis
Michigan Tech
Arizona State
Montana State - Bozeman
Penn State
Taylor University
U Colorado, Boulder
U Hawaii at Manoa
U Michigan
Worcester Polytechnic
New Mexico State
Utah State

2005 NS-4
U Cincinnati
U Minnesota
U Central Florida
Santa Clara U
Cornell University - W
U Missouri - Rolla
Texas A&M
New Mexico State
Washington U - St. Louis
Utah State
UT Austin

2007 NS-5
Boston U
U Colorado at Boulder - W
Montana State U
Michigan Tech
Minnesota U
Penn State U
Washington U in St. Louis
UT at Austin
Texas A&M U
Santa Clara U
Utah State U

2009 NS-6
Georgia Tech
University of Hawaii - M
MIT
Montana State University
Missouri S&T
Michigan Tech - W
Santa Clare University
University of Central Florida
University Minnesota
Cornell University - M
Washington University (St Louis) - M

2011 NS-7
Georgia Tech - W
MIT
Montana State University
Missouri S&T
St Louis University - M
Boston University
University of Michigan - M
University of Texas - W
University of Buffalo
University of Maryland

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Questions?